Inconspicuous Minifilament Eruptions as the Source of Conspicuous Extreme Ultraviolet (EUV) Outflows in the Solar Atmosphere

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Abstract

We used EUV images from the Atmospheric Imaging Assembly (AIA) and magnetograms from the Helioseismic and Magnetic Imager (HMI), both onboard the Solar Dynamics Observatory (SDO), to search for the low-solar-atmospheric sources of nine blueshifted outflow events found by the EUV (Extreme Ultraviolet) Imaging Spectrometer (EIS) onboard Hinode. Five events were in the northern polar region and four were near the equator. For seven of the events, we find eruptive activity consistent with a minifilament eruption occurring at the time and location of the observed blueshift event, while the remaining two events were too feeble for us to make a determination. These minifilament eruptions are similar to but feebler than those previously found to make coronal jets. In three cases, we identify a jet-like spire emanating from the minifilament-eruption region, while in the other six events such a spire is too faint to be detected or is absent. We find the erupting minifilaments to have lengths of ~9K km and proper motion speeds of ~30 km/s near their eruption onset time, values which are within size and velocity ranges found previously for obvious erupting minifilaments in the production of obvious jets. In one of these events we find evidence of a minifilament candidate that is too close to the background noise level to properly determine if it is the source of the EIS outflow, but if it is, it suggests that omnipresent dynamic features in the lower solar atmosphere may create outflows, conveying that this could be the source of the solar wind. For two of the low-latitude cases, HMI magnetograms show evidence of flux cancellation among weak magnetic flux patches at about the eruption onset time, again consistent with what has been found for many stronger coronal jets. The fluxes for the other two low-latitude events were too close to the magnetogram noise level for us to make a determination. Our observations support that hard-to-detect erupting minifilaments can make inconspicuous coronal jets that result in conspicuous coronal outflows seen by EIS, confirming an earlier study by Sterling et al. (2022, ApJ, 940, 85). We strengthen the conclusion of that study by finding evidence that cancellation of flux near HMI's detection limit results in erupting minifilaments that produce inconspicuous jets and conspicuous EIS-detected coronal outflows.

Background

In 2020 the Sun was rastered and evidence of plasma outflows was found. Schwanitz et al. (2021) observed the locations of fourteen localized and enhanced outflows using the Doppler data from this rastering and performed an initial assessment for the coronal source of each event. Of these fourteen events, only five had Hinode X-ray imaging data to allow for more detailed observing of these areas. Sterling et al. (2022) investigated these five events in greater detail and found that they corresponded to inconspicuous X-ray jets that are formed from the eruption of erupting minifilaments (EMFs), which is the same case for typical coronal jets (Sterling et al. 2015). Those five events were all in the solar polar region, and so it was not possible for detailed investigations of the magnetic field changes at the jet bases. Here we examine the nine Schwanitz et al. (2021) that were not examined by Sterling et al. (2022). We use AIA imaging data to investigate whether these regions also might result from hard-to-detect coronal jets. Four of our nine events were at low altitude, allowing for investigation of magnetic field changes at the EIS-outflow locations. Properly understanding the source of this type of event is important because if there are many such events happening simultaneously on an even smaller scale, it is possible that it could be the source of the constant solar wind.

Instrument and Data

The instrumentation used to image these events is the AIA and the HMI onboard SDO. We used the AIA wavelengths 171, 193, 211, and 304 Å at a cadence of twelve seconds, and for the HMI magnetogram we used a cadence of forty-five seconds. In their paper, Schwanitz et al. (2021) numbered each of the events 1-14. Sterling et al. (2022) observed events 1-5 while we look at the remaining events 6-14. **Table 1** provides more information about these nine events.

Event	EIS Time (UT)[a]	EIS Size ($arcsec^2$)[a]	Event Location
6	4-Feb-2020 13:55:37	699	Pole region
7	4-Feb-2020 13:25:13	179	Pole region
8	4-Feb-2020 13:02:03	224	Pole region
9	4-Feb-2020 14:09:27	378	Pole region
10	4-Feb-2020 14:30:13	464	Pole region
11	8-Feb-2020 12:27:20	108	Near equator
12	11-Feb-2020 12:50:35	113	Near equator
13	11-Feb-2020 13:08:24	850	Near equator
14	11-Feb-2020 12:48:12	539	Near equator

Table 1: Table of dates, times, sizes, and locations of each of the outflow events. [a]From Table 2 of Schwanitz et al. (2021).

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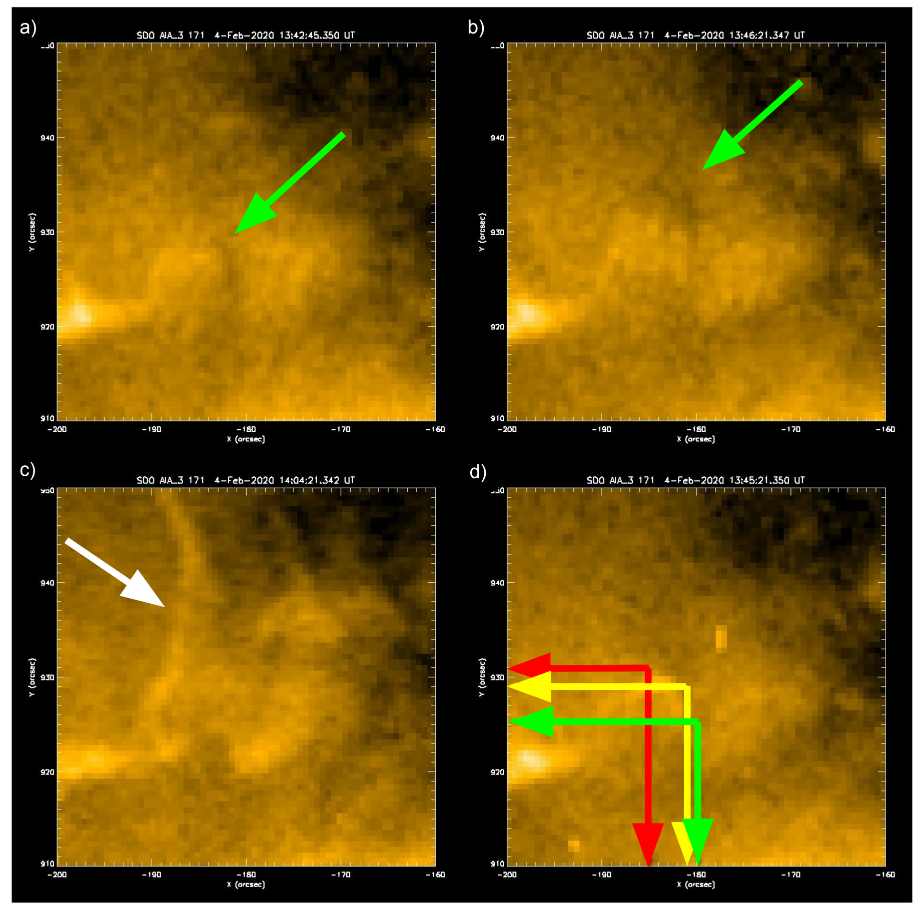

Figure 1:Snapshots of the source of EIS outflow event 6 in AIA 171 Å. Green arrows point to the cool material that is consistent with erupting minifilaments and the white arrow points to the spire resulting from the event. Panel a) depicts the minifilament before it erupts, panel b) shows the obvious minifilament movement as it is erupting, and panel c) shows the resulting jet spire, which is the source of the EIS event. d) shows a demonstration of how the coordinates for length and proper motion were obtained. Each frame shows this location on 4-Feb-2020, at 13:42, 13:46, and 14:04 UT.

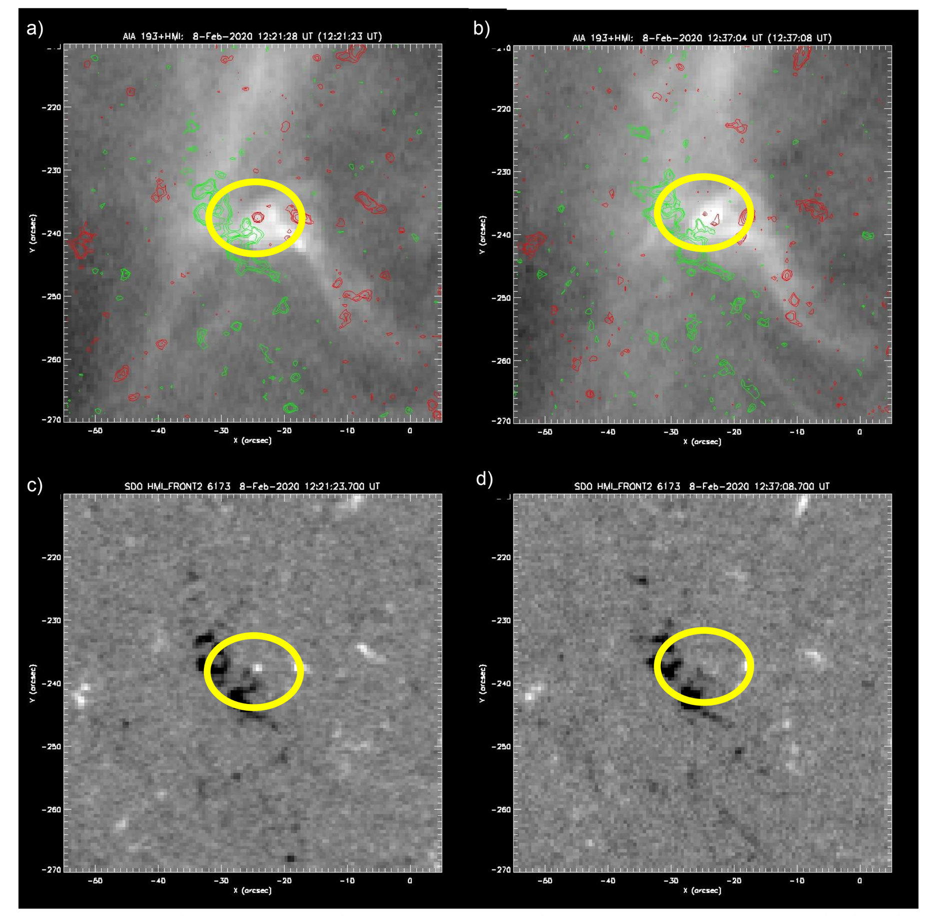

Figure 2: Snapshot of the source of event 11. Panels a) & b) show the FOV before and after the outflow event in 193 Å with an HMI contour map overlay. Panels c) & d) depict the magnetograms of roughly the same times as a) & b) (within a few seconds). Flux cancellation is seen as the positive flux (white patch) disappears at the right time and location for the outflow event, consistent with what has been observed for jets (Panesar et al. 2016). Each frame shows this location on 8-Feb-2020 at 12:21 and 12:37 UT.

Event	Appearance	EMF Size (km)[a]	EMF Velocity ($km\ s^{-1}$)[a]
6	Dynamic EMF that gives way to a jet-like spire.	7,000 ± 700	50 ± 20
7	Minifilament is too feeble to detect, but there is a feeble and inconspicuous jet that is consistent with jets created by EMFs at the correct time and location to be source of the event.	Uncertain	Uncertain
8	Very feeble EMF candidate, too close to background noise to say.	N/A	N/A
9	EMF with rotating ("unwinding") movement. Appears to be a contained eruption.	14,300 ± 300	29 ± 10
10	Brightening consistent with inconspicuous jet created through an EMF.	7,200 ± 2,400	49 ± 30
11	Appears to be a confined eruption caused by EMF.	7,500 ± 200	18 ± 10
12	Dynamic minifilament motion with brightening consistent with EMF origin.	7,000 ± 400	18 ± 10
13	Minifilament eruption at the time of the event. Base of the eruption brightens and a spire is created coming from the location.	Uncertain	Uncertain
14	EMF is either too feeble to detect or not present.	N/A	N/A

Table 2: Table of attributes of the sources identified for each event, including source appearance, size (length), and velocity. Velocity is measured against the solar disk. [a]Measured from AIA images with 1σ standard deviation in location. Events 7 and 13 were consistent with an EMF presence but we were unable to properly measure them. For event 8 we found an EMF candidate but it was too feeble to definitively say that it was an EMF, and for event 14 we were unable to locate the minifilament or structures consistent with its presence.

Results

Figures 1 and **2** show results for two of our events, events 6 and 11, and we summarize all of our events in **Table 2**. Event 6 is located at the northern solar pole, so we were unable to get proper HMI data on it. As it stands, it is an EMF that creates an obvious jet spire that was picked up by EIS as the outflow event; see **Figure 1**. Event 11 is located near the equator which allows us to observe the magnetic flux of the area at the time of the outflow event, which has been shown can create EMFs (Sterling et al. 2015); see **Figure 2**. We were able to measure the size and velocity of the minifilaments in five of the seven events in which we determined the source of the outflow, and the measurements are displayed in **Table 2**. The remaining two events were not conclusive and we were unable to make a determination about the minifilament's length or velocity.

Discussion

Our data suggests EMFs can be the sources of plasma outflow events like the ones found and recorded by Schwanitz et al. (2021). More specifically, our data shows that these conspicuous events can be caused by inconspicuous jets and brightenings that are consistent with having been created by a minifilament eruption. Following this line of logic, it stands to reason that even more inconspicuous jets could be occurring on even smaller scales that cannot be detected. If this is the case, it is entirely possible that numerous, omnipresent dynamic features, such as small-scale jet-like eruptions, in the lower solar atmosphere may create outflows. This in turn suggests that these types of dynamic features could be the elusive source of the solar wind (Raouafi et al. 2023) which may be fueled by these outflows.

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